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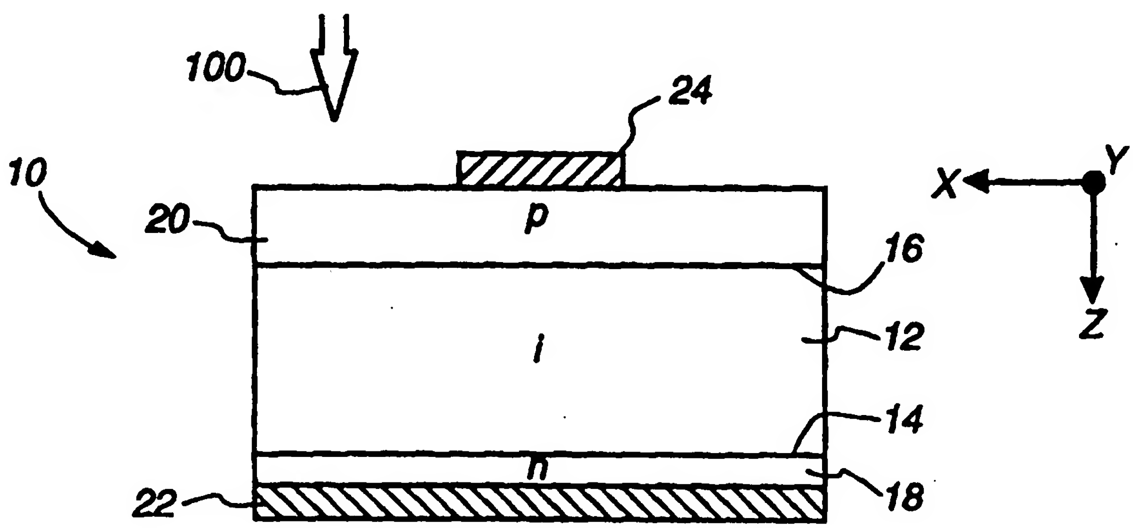

(57) Abstract

A p-i-n semiconductor diode is provided that is useful for detecting X-ray radiation, wherein an i-type InGaN semiconductor layer (12) has a first surface portion (14) and a second surface portion, wherein a p-type semiconductor region (20) exists on this first surface portion (16), wherein an n-type semiconductor region (18) exists on this second surface portion (14), wherein a first electrical contact (24) is located on the p-type semiconductor region (20), and wherein a second electrical contact (24) is located on the n-type semiconductor region (18). In addition a multi-pixel X-ray detector array is provided wherein each pixel is constructed and arranged as stated above, and in which the above described first and second electrical contacts (24, 18) comprise the column and row pixel-interrogation conductors of the array.

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X-RAY DETECTOR

CROSS REFERENCE TO RELATED APPLICATION

Provisional patent application Serial Number 08/530,507 filed September 19, 1995.

This invention was made with government support under Grant No. DE-FG03-95ER86024 awarded by the Department of Energy. Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

Field of the Invention:

This invention is relates to X-ray detectors, and more particularly, to X-ray detectors that include a wide-bandgap semiconductor alloy, or alloys, and are adapted for uncooled operation.

Description of the Related Art:

The term X-ray detection as used herein is meant to include the detection of electromagnetic radiation whose wave length is generally in the range of from about 0.1 angstroms to about 100.0 angstroms.

As is known, the use of X-rays to irradiate objects, and thus form a visual picture of the object in accordance with the absorption of the X-rays, involves subjecting the object to either continuous or pulsed X-ray radiation. In order to provide a picture of the X-ray absorption by the object, a medium, such as photographic film, is positioned downstream of the object to record the downstream X-ray intensity during the time interval that the object is radiated by the X-rays.

X-ray detectors should be radiation-sensitive, radiation-hard, and should not be physically bulky. A number of semiconductor detectors have been developed for the detection of X-ray radiation. Examples are X-ray detectors that are made from c-Si, Ge, CdTe, CdZnTe, GaAs, HgI_2 and hydrogenated amorphous Si (a-Si:H). Silicon (Si) based detectors (c-Si and a-Si:H) are popular, but are known as being the least efficient for penetrating X-rays and gamma rays due to the low Z number in silicon. Germanium (Ge) detectors must be operated at cryogenic temperatures in order to reduce thermally-generated leakage current, and in order to reduce Li diffusion in Li-diffused detectors. Although micro-coolers have been developed, they add cost, weight and power consumption, and they generate vibrations.

Much work has been done in developing detectors that are made from CdTe and H_gI_2. Only moderated resolution (1.1 keV at 5.9 keV) has been achieved with CdTe, and polarization has been a persistent problem. Furthermore, both Cd and Te are expensive. H_gI_2 has high efficiency for the detection of X-rays and gamma rays, and has good resistance to radiation damage. However, this material is hard to grow to useful size. This material is also too soft and too chemically active, resulting in handling and stability problems. In addition, Cd, Te, Hg and iodine have harmful isotopes for environmental and human safety concerns.

Position-sensitive and physically large X-Y area detectors (X feet by Y feet) are desirable for use in X-ray crystallography, as well as in medical and industrial radiography; for example, as an electron "film" substitute for photographic film. Such an electron "film" would have broader dynamic range and would provide real-time digital-read-out capability.

However, a large, multi-pixel, array of X-ray detectors that requires vacuum cryostat and low temperature would be extremely bulky and would be costly to use.

Therefore, it is desirable to provide an X-ray detector that is superbly radiation hard, that is highly sensitive, that operates at room temperature, that has low operating and material cost, that is environmentally sound, and that can be built to form a large, multi-pixel, planar, array of X-ray detectors.

U.S. Patents 4,614,961, 4,616,248, and 5,182,670 by M. A. Kahn et al, and U.S. Patent 5,278,435 to Van Hove et al are generally of interest. Patent '961 describes a UV detector that is prepared from AlGaN by the use of Metal-Organic-Chemical-Deposition (MOCVD). This detector comprises an aluminum oxide substrate, a single crystalline aluminum nitride layer, an aluminum nitride buffer-layer, and a single crystalline aluminum gallium nitride layer. The assembly of patent '248 comprises an aluminum oxide substrate, a single crystalline gallium nitride layer, a single crystalline AlGaN layer, and a very thin layer of cesium. The teachings of patents '670 and '435 again relate to devices using AlGaN layers.

SUMMARY OF THE INVENTION

The present invention provides a single-pixel X-ray semiconductor detector, and a multiple-pixel array of semiconductor X-ray detectors, that are radiation-hard, that are radiation-sensitive, and that operate at room temperature. The present invention finds utility in the fields of radiography, nuclear physics research, X-ray crystallography, X-ray and gamma-ray astronomy and environmental monitoring.

In order to form an X-ray detector in accordance with this invention, an active i-type semiconductor layer of InGaN is located between an upper p-type AlGaN semiconductor layer that comprises a window to X-ray radiation, and a lower n-type GaN layer. In accordance with the invention, the X-ray detector semiconductor assembly is based upon the material (InGa)N, wherein this material is preferably grown on a nearly latticed-matched substrate. For example, for the alloy InGaN, wherein the alloy comprises 16% In and 84% Ga, the lattice constant is about 3.246 angstroms, very close to the lattice constant of 3.252 of a ZnO substrate.

The X-ray detector comprises a p-i-n semiconductor diode that is reverse voltage biased, such that in the presence of X-ray radiation an electrical current flows external to the detector.

A number of individual single-pixel X-ray detectors are arranged in a multi-pixel array, and each individual pixel of the array is electrically read-out by the intersection of an active row-conductor and an active column-conductor that operate to apply a reverse bias to the one detector pixel that is physically located at the intersection of the active row-conductor and the active column conductor.

The X-ray detector of the present invention has little or no memory, and as a result, the X-ray detector is electrically read-out during the time interval that an object to be investigated by the use of X-rays is being radiated by the X-rays. An example, electrical read-out occurs during an X-ray pulse interval that is usually less than one second long.

While X-ray detectors in accordance with this invention include a p-type layer that preferably serves

as a window, or entry side for the X-ray radiation that is to be detected, this is not to be taken as a limitation on the spirit and scope of the invention, since the X-ray radiation that is to be detected can also enter the X-ray detector from its opposite side; i.e., through the n-type layer.

An object of this invention is to provide a p-i-n semiconductor diode that is useful for detecting X-ray radiation, wherein an i-type InGaN semiconductor layer has a first surface portion and a second surface portion, wherein a p-type semiconductor region exists on this first surface portion, wherein a n-type semiconductor region exists on this second surface portion, wherein a first electrical contact is located on the p-type semiconductor region, and wherein a second electrical contact is located on the n-type semiconductor region.

An additional object of the present invention is to provide a multi-pixel X-ray detector array wherein each pixel is constructed and arranged as stated above, and in which the above-described first and second electrical contacts comprise the column and row pixel-interrogation conductors of the array.

These and other features, objects and advantages of the present invention will be apparent to those of skill in the art upon reference to the following detailed description of preferred embodiments of the invention, which description makes reference to the drawing.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side view of a single-pixel, p-i-n semiconductor diode X-ray detector in accordance with the present invention, as seen in the X-Z plane.

FIG. 2 is a side view of another embodiment of a single-pixel, p-i-n semiconductor diode X-ray detector in accordance with the present invention, as seen in the X-Z plane.

FIG. 3 is a top or X-Y plane view of a circular detector in accordance with FIG. 1.

FIG. 4 shows a circuit that is used to reverse-bias the p-i-n diode X-ray detector of FIGS. 1, or the X-ray detector of FIG. 3.

FIG. 5 shows a physically large X-Y array of X-ray detectors that comprises the number "n" of detector columns, and the number "m" of detector rows.

FIG. 6 is an enlarged side view of the detector array of FIG. 5, taken in the X-Z plane, showing three individual X-ray pixel detectors, along with three linear Y-direction column-conductors and one linear X-direction row-conductor, which conductors are used to interrogate the three detector pixels.

FIG. 7 is a top or X-Y plane view of a circular detector in accordance with FIG. 2.

FIG. 8 is a side sectional view in the X-Z plane of another form of p-i-n diode X-ray detector of the present invention that is similar to FIG. 1 in which an interdigitated finger electrode configuration is provided.

FIG. 9 is a side sectional view in the X-Z plane of another form of an X-ray detector of the present invention wherein the n-i-p regions of the X-ray detector are formed as separate regions within a single layer of InGaN.

FIG. 10 is a side sectional view in the X-Z plane of another form of an X-ray detector of the invention, wherein the top and bottom surfaces of an insulating InGaN layer are each provided with a metal contact layer.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring initially to FIG. 1, a single-pixel, p-i-n semiconductor diode X-ray detector of the present invention is generally designed as 10. A ZnO substrate is not shown in FIG. 1.

As will be described, the single-pixel X-ray detectors that are shown and described relative to the various embodiments of this invention can easily be fabricated into large, multi-pixel, and generally X-Y planar, detector arrays that can be read-out pixel-by-pixel in order to form a visual display of an X-Y coordinate X-ray radiation pattern.

X-ray detector 10 of FIG. 1 comprises a semiconductor body 12 of single crystalline i-type conductivity (intrinsic) InGaN, having two opposed and generally parallel planar surfaces 14 and 16. On surface 14 of body 12 is a generally uniform Z-thickness semiconductor layer 18 of n-type conductivity GaN. On surface 16 of body 12 is a generally uniform Z-thickness semiconductor layer 20 of p-type conductivity AlGaN. A generally uniform thickness first metal contact 22 of Al/Ti is located on the lower

surface of GaN layer 18, and a generally uniform thickness second metal contact 24 of Au/Ti is located on the upper surface of AlGaN layer 20.

As viewed from above in the X-Y plane, X-ray detector 10 may be of a number of geometric shapes, including circular, square and rectangular. For example, FIG. 3 is a top view in the X-Z plane of a circular version of FIG. 1's X-ray detector 10.

In a preferred embodiment of the invention, but without limitation thereto, the semiconductor material $In_{0.16}Ga_{0.84}N$ was used to form i-type layer 12. This material has an X-ray absorption that is comparable to that of Ge, assuming the material is working at the photoelectric absorption region; i.e., in the spectral region where a photon is converted into electron/hole pairs. Also, this material has an energy bandgap of about 3.16 eV, and a lattice constant of about 3.246 angstroms.

Upper p-type AlGaN layer 20 serves as a window to allow X-ray radiation 100 that travels in the Z direction to enter i-type InGaN body 12. An undoped InGaN layer, or body 12, tends to be n-type. However, a controlled amount of Mg, Zn, Cd or Ca may be added to body 12 to make it insulating.

Between n-i interface 14 and at the i-p interface 16, the In, Ga and Al composition can be graded to achieve a good electric field profile.

Generally, X-ray detector 10 surpasses the performance characteristics of cooled Ge-based X-ray detectors in the following ways. Because of the much wider bandgap of InGaN body 12, the thermal background of carriers is small, thus making room-temperature and

low noise operation possible. Detector 10 is not responsive to most of the visible light spectrum, and is easy to use; i.e., it is user-friendly. In addition, an evacuated container is not needed to transport detector 10. An X-ray detector without cryostat and liquid nitrogen is more carefree, less bulky and more economical to operate. Furthermore, because there is no need for vacuum and cryostat, it is feasible to build large detector arrays (several feet square) to replace X-ray films that are currently used in radiography and crystallography.

Referring now to FIG. 2, another form of an X-ray detector of the present invention is generally designed as 30. Detector 30, as viewed from above, is generally rectangular. However, the X-Y shape of detector 30 may take a variety of geometric shapes, and FIG. 7 is a top view of a circular detector 30.

X-ray detector 30 comprises a generally flat and uniform Z-direction thickness substrate 32 of ZnO having an upper surface 34. On the upper surface 34 of substrate 32 is a generally uniform thickness semiconductor buffer-layer 35 of GaN or AlN. A generally uniform thickness n-type GaN semiconductor layer 38 is located on the upper surface 42 of GaN buffer-layer 35. A relatively thick and uniform thickness semiconductor layer 40 of i-type conductivity (electrically insulating) InGaN is located on only the portion 50 of the upper surface 44 of n-type GaN 38. A generally uniform thickness layer 51 of p-type conductivity A1GaN semiconductor is located on the upper surface 52 of i-type InGaN layer 40.

A first metal contact, or contact layer 53 of Al/Ti, is located on a portion 55 the upper surface 56 of n-type GaN layer 38. A second metal contact or

layer 59 of Au/Ti is located on the upper surface 60 of p-type AlGaN layer 51.

Use of ZnO substrate 32 in the FIG. 2 detector is optional. It is known that ZnO material attenuates X-ray radiation, and should detector 30 be used with X-ray radiation entering detector 30 from the under side, i.e., through GaN buffer-layer 35, it may be desirable to remove ZnO substrate 32 after detector 30 has been fabricated. In addition, an alternate material for substrate layer 32 is aluminum oxide, i.e., Al_2O_3.

In operation, a reverse bias, or negative DC voltage, is applied to contact 24 of FIGS. 1 and 3, or to contact 59 of FIG. 2, as a positive DC voltage is applied to contact 22 of FIG. 1, or to contact 53 of FIG. 2. As a result, the p-i-n X-ray detector structure 18,12,20 of FIG. 1, and 38,40,51 of FIG. 2, is reverse-biased.

When reverse-biased detector 10 of FIGS. 1 and 3, or reverse-biased detector 30 of FIG. 2, is thereafter subjected to X-ray radiation, preferably X-ray radiation that travels in the Z-direction, electron/hole pairs are generated within the i-type InGaN layers 12,40 of detectors 10,30.

As the intensity of the X-rays that are sensed by an X-ray detector in accordance with this invention increases, the density of the electron-hole pairs that are generated within i-type InGaN layers 12,40 also increases. Thus, from pixel-to-pixel of a multi-pixel detector array in accordance with this invention, variations in X-ray intensity, sometimes called shades of grey, can be detected.

FIG. 4 show an electrical circuit that operates to reverse voltage bias detector 10 of FIG. 1, and additionally shows the use of a current sensitive means 70 to detect the external current that flows when detector 10 is subjected to X-ray radiation. The DC bias voltage 71 of about 15 VDC that is applied to contacts 24,22 of detector 10, or to contacts 59,53 of FIG. 2's detector 30, cause an external current to flow to external current sensitive means 70 during the time interval in which detector 10 or detector 30 is subjected to X-ray radiation. Other DC bias voltage magnitudes can be used, depending upon the use-application, and/or the thickness of the X-ray detector.

With reference to FIG. 5, this figure shows a physically large X-Y detector array 81 that comprises the number "n" of detector columns and the number "m" of detector rows, wherein "n" and "m" are both integers that may, or may not be of equal magnitude. In this figure, the first and the last detector columns C1 and Cn, and the first and the last detector rows R1 and Rm are identified by appropriate legends. As is apparent, detector array 81 comprises the number "n-times-m" of individual X-ray detectors 80 that are constructed and arranged in accordance with this invention. As is well known, in order to read-out array 81, the number "n" of column-conductors, and the number "m" of row-conductors are provided. In FIG. 5, one column-conductor Cn-3, and one row-conductor Rm-2 are shown. When pixel interrogation voltages are applied to one column-conductor and one row-conductor, for example, column-conductor Cn-3 and row-conductor Rm-2, only one pixel is read-out (for example, pixel 82 of FIG. 5).

In accordance with this invention, the above-described eolumn-conductors of FIG. 5 may comprise

conductor 22 of FIG. 1, or conductor 53 of FIG. 3., whereupon the above described row-conductors will comprise conductor 24 of FIG. 1, or conductor 59 of FIG. 2. Of course, this configuration can be reversed from the above-stated order; i.e., the column conductors may comprise p-i-n diode conductors 24 or 59, as the row conductors comprise p-i-n diode conductors 22,53.

FIG. 6 is an enlarged side view of the detector array 81 of FIG. 5, taken in the X-Z plane, and showing three individual X-ray pixel detectors 94,95,96 of the present invention, along with the three linear Y-direction column-conductors 91,92,93 and one linear X-direction row-conductor 90, which conductors are used to interrogate the three detector pixels 94,95,96 in the manner above described.

As an example of size, the individual pixels 80 of array 81 may be generally in the multimicron-by-multimicron or centimeter-by-centimeter size, and an example is in the range of from about 3 mm to 5 mm square, as is measured in the X-Y plane.

FIG. 6 shows that the three layers (i.e., n-type, i-type, p-type) of each individual X-ray detector 94,95,96 are supported by an inert substrate member 97 through which column-conductors 91,92,93 extend. Each of the detector pixels 80 of FIG. 5 is surrounded by a small Z-direction space 98 that may be formed in a large three-layer semiconductor member, as by the use of chemical etching, laser cutting, or mechanical cutting.

Space 98 may also be filled by a passive material, such as insulating AlN, Al_2O_3 or SiO_2, or a passive

layer of AlN, Al_2O_3 or SiO_2 and a filler of polymer or epoxy.

FIG. 8 is a side sectional view in the X-Z plane of another form of a p-i-n diode X-ray detector 80 of the present invention that is similar to FIG. 1. However, in FIG. 8, an interdigitated finger electrode configuration is shown wherein p-type layer 22 comprises five individual sections 118, and each p-type section 118 has its own individual electrical contact 122. While five sections 118 are shown, this number is not critical to the invention.

The detector assembly of FIG. 8 is again reverse biased by connecting its contact 24 to a source of positive DC voltage. The contacts 122 are alternately connected to a source of negative DC voltage by way of conductors 200,201.

For energy dispersion applications, the resolution of the X-ray detector can be improved by using the above-described interdigitated finger electrodes. A small magnitude voltage that is supplied across conductors 200,201 functions as a grid to remove the collection of the slow moving carriers (normally holes), thus enhancing the resolution of the X-ray detector.

FIG. 9 is a side sectional view in the X-Z plane of another form of an X-ray detector 300 of the present invention, wherein the n-i-p regions of the X-ray detector are formed as separate regions within a single layer 301 of InGaN. As can be seen, detector 300 is generally of the same geometric shape as detector 10 of FIG. 1.

More specifically, and with reference to FIG. 9, as layer 301 of InGaN is grown, the doping is altered so that its major midportion 302 comprises i-type conductivity, so that its relatively thin upper portion 303 comprises higher n-type conductivity, and so that its relatively thin lower portion 304 comprises p-type conductivity. As with other embodiments of the invention, the single-pixel of the FIG. 9 X-ray detector is readout by applying a reverse-bias voltage to contacts 305 and 306.

In the manufacture of X-ray detector 30 of FIG. 2, the various layers of the detector are grown on substrate 32 using the well-known process of MOCVD.

Because the lattice mismatch between GaN buffer-layer 35 and ZnO substrate 32 is very small, good-quality single crystalline GaN can be deposited on ZnO substrate 32.

N-type GaN layer 38 is grown from triethylgallium (TEG) or trimethylgallium (TMG) and ammonia (NH_3), with the addition of a controlled amount of Si.

Thereafter, i-type InGaN layer 40 is grown from TEG, TEI (triethylindium), or TMG and TMI (trimethylindium), and ammonia at a temperature of about 750-degrees C. Controlled amounts of Mg, Zn, Cd or Ca are introduced to change the compensation level so as to deposit i-type material 40.

The partially-manufactured detector 30 is then heated to about 1030-degrees C in order to grow p-type conductivity AlGaN layer 51 using TEA, TEG, NH_3 and Cp_2Mg with hydrogen or helium dilution.

After the layer depositions as above described, partially-manufactured detector 30 is annealed in dry nitrogen at about 700-degrees C, and then cooled down.

Electrical contact layers 53 and 59 are deposited by any well-known technique, such as vacuum evaporation or sputtering. If desired, contact layers 53,59 can be further annealed in order to improve their characteristics.

While a MOCVD process is used, other processes or methods, such as chloride transport CVD, can also be used.

In preferred embodiments of X-ray detectors in accordance with this invention, the percentage-amount "x" of the element "In" that is contained in the semiconductor material InxGa1-xN that comprises active layers 12,40 of FIGS. 1 and 3, respectively, is in the range from about 0% to about 40%. While higher percentages of the element "In" may be desirable for the active layers 12,40, these higher percentages are generally more difficult to achieve. In a preferred embodiment of the invention, doping of the detector's active InGaN layers 12,40 was provided in order to increase the resistivity of layers 12,40, and in this manner, a resistivity generally above 10^7 ohm-cm was provided.

For imaging applications, 0% of "In" within the InGaN layer will work in a satisfactory manner. Another desirable range is from about 15% to about 40%.

The Z-direction thickness of the resistive InGaN i-type layer of X-ray detectors in accordance with this invention is dictated by the X-ray absorption coefficient, and is about 1mm.

The Z-direction thickness of the GaN n-type layer of X-ray detectors in accordance with this invention is about 3.0 micrometer.

The Z-direction thickness of the AlGaN p-type layer of X-ray detectors in accordance with this invention is about 1.0 micrometer.

This invention has been described in detail while making reference to preferred embodiments of the invention. However, since it is apparent that those of skill in the art to which this application pertains will readily visualize yet other embodiments that are within the spirit and scope of this invention, the foregoing detailed description is not to be taken as a limitation on the spirit and scope of this invention.

What is claimed is:

CLAIMS

1. A p-i-n semiconductor diode useful for detecting X-ray radiation, comprising:

an i-type InGaN semiconductor layer having a first surface portion and a second surface portion;

a p-type semiconductor region on said first surface portion;

an n-type semiconductor region on said second surface portion;

a first electrical contact on said p-type semiconductor region; and

a second electrical contact on said n-type semiconductor region.

2. The semiconductor diode of claim 1 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is in the range of about 0 percent to about 40 percent.

3. The semiconductor diode of claim 2 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is about 16 percent.

4. The semiconductor diode of claim 1 wherein:

said p-type semiconductor region comprises AlGaN; and

said n-type semiconductor region comprises GaN.

5. The semiconductor diode of claim 4 wherein:

said first electrical contact comprises Au/Ti; and

said second electrical contact comprises Al/Ti.

6. The semiconductor diode of claim 5 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is in the range of about 0 percent to about 40 percent.

7. The semiconductor diode of claim 6 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is about 16 percent.

8. The semiconductor diode of claim 6 wherein said p-type AlGaN contains Mg doping, and i-type InGaN contains a doping selected from the group Mg, Zn, Cd and Ca.

9. The semiconductor diode of claim 1 wherein:

said p-type semiconductor region is p-type AlGaN or p-type GaN; and

said n-type semiconductor region is selected from the group AlGaN or GaN.

10. The semiconductor diode of claim 1 including:

a buffer-layer and an inert substrate member intermediate said n-type semiconductor region and said first electrical contact such that said buffer layer is adjacent to said n-type semiconductor region.

11. The semiconductor diode of claim 10 wherein:

said buffer layer is GaN or AlN; and

said substrate member is selected from the group ZnO and Al_2O_3.

12. The semiconductor diode of claim 11 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is in the range of about 0 percent to about 40 percent.

13. The semiconductor diode of claim 12 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is about 16 percent.

14. The semiconductor diode of claim 13 wherein:
said p-type semiconductor region comprises AlGaN or GaN; and
said n-type semiconductor region comprises AlGaN or n-type GaN.

15. The semiconductor diode of claim 14 wherein:
said first electrical contact comprises Au/Ti; and
said second electrical contact comprises Al/Ti.

16. A generally flat-panel X-ray detector array comprising:

a plurality of individual pixel-detectors that are physically arranged in a geometric pattern so as to form said detector array having a plurality Y of individual pixel-detector-columns and a plurality X of individual pixel-detector-rows, said numbers X and Y being integers;

a plurality Y of column-conductors, each of said column-conductors cooperating with individual pixel-detectors within one of said detector-columns;

a plurality X of row-conductors, each of said row-conductors cooperating with individual pixel-detectors within one of said detector-rows;

wherein each of said individual pixel-detectors comprises,

an i-type InGaN semiconductor layer having a first surface portion and a second surface portion,

a p-type semiconductor region on said first surface portion, and

an n-type semiconductor region on said second surface portion,

wherein said plurality Y of column-conductors electrically contact one of said p-type semiconductor region or said n-type semiconductor region; and

wherein said plurality of row-conductors eclectically contact the other of said p-type semiconductor region or said n-type semiconductor region.

17. The X-ray detector array of claim 16 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is in the range of about 0 percent to about 40 percent.

18. The X-ray detector array of claim 17 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is about 16 percent.

19. The X-ray detector array of claim 17 wherein:
said n-type semiconductor region comprises GaN; and
said p-type semiconductor region comprises AlGaN or GaN.

20. The X-ray detector array of 19 wherein:
said plurality Y of column-conductors electrically contact said p-type semiconductor region and are Au/Ti or AuNi; and
said plurality of row-conductors eclectically contact said n-type semiconductor region and are Al/Ti.

21. The X-ray detector array of claim 16 wherein:
said p-type semiconductor region is GaN; and
said n-type semiconductor region is selected from the group AlGaN and GaN.

22. The X-ray detector array of claim 21 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is in the range of about 0 percent to about 40 percent.

23. The X-ray detector array of claim 22 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is about 16 percent.

24. A p-i-n semiconductor diode that is sensitive to X-ray radiation, comprising:

an i-type InGaN semiconductor layer having a first surface portion that is doped to provide a p-type semiconductor region, and having a second surface portion that is doped so as to provide an n-type semiconductor region;

a first electrical contact on said p-type semiconductor region; and

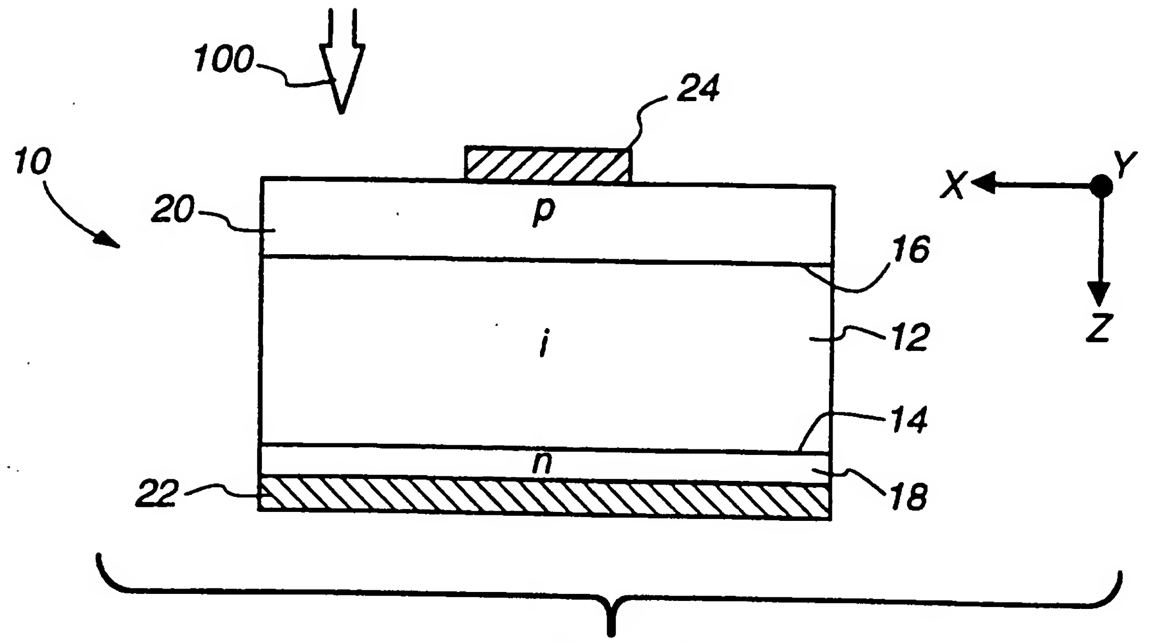
a second electrical contact on said n-type semiconductor region.

25. The semiconductor diode of claim 24 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is in the range of about 0 percent to about 40 percent.

26. The semiconductor diode of claim 25 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is in the range of about 15 percent to about 40 percent.

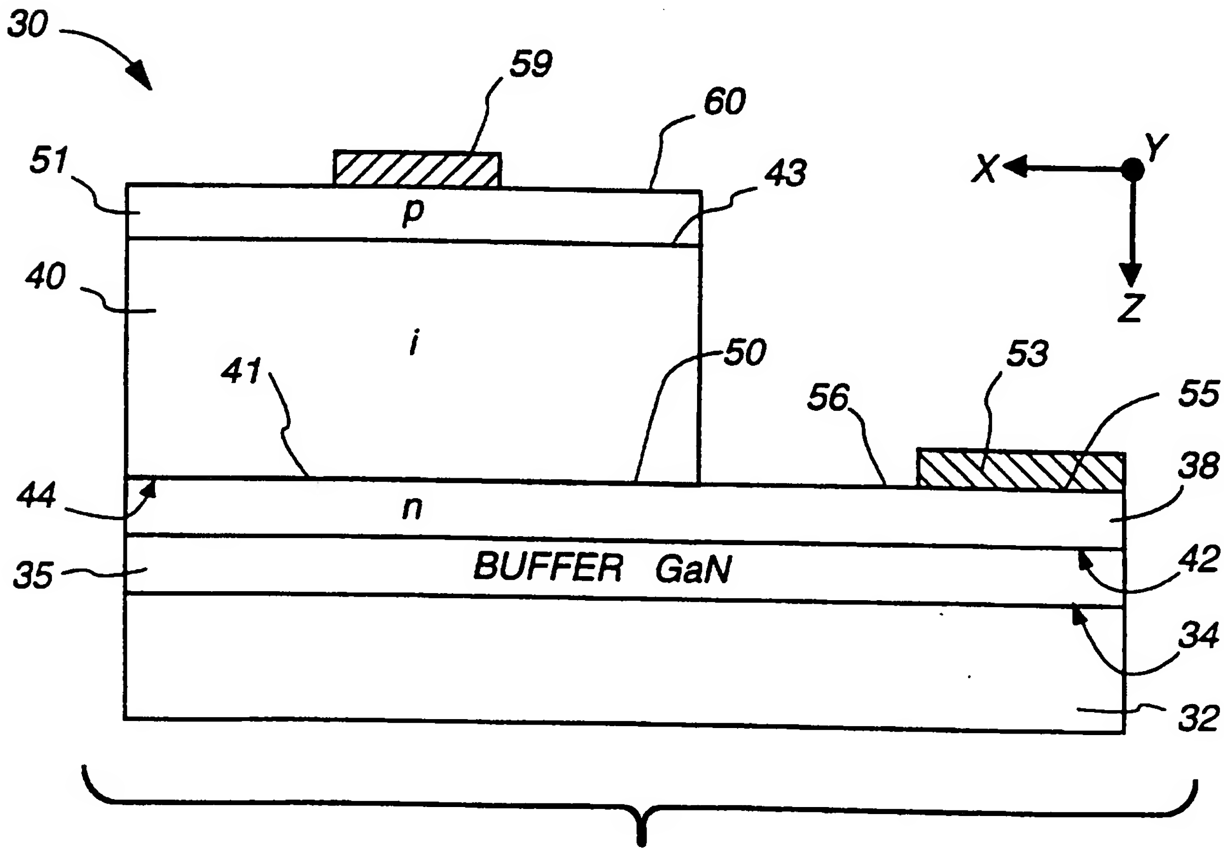
27. The semiconductor diode of claim 26 wherein said i-type InGaN semiconductor layer comprises $In_xGa_{1-x}N$, wherein x is about 16 percent.

1/5



100
24
10
20
p
16
i
12
14
n
22
18
X
Y
Z

Fig. 1



30
59
60
51
43
p
40
i
41
50
53
56
55
44
n
38
BUFFER GaN
35
42
34
32
X
Y
Z

Fig. 2

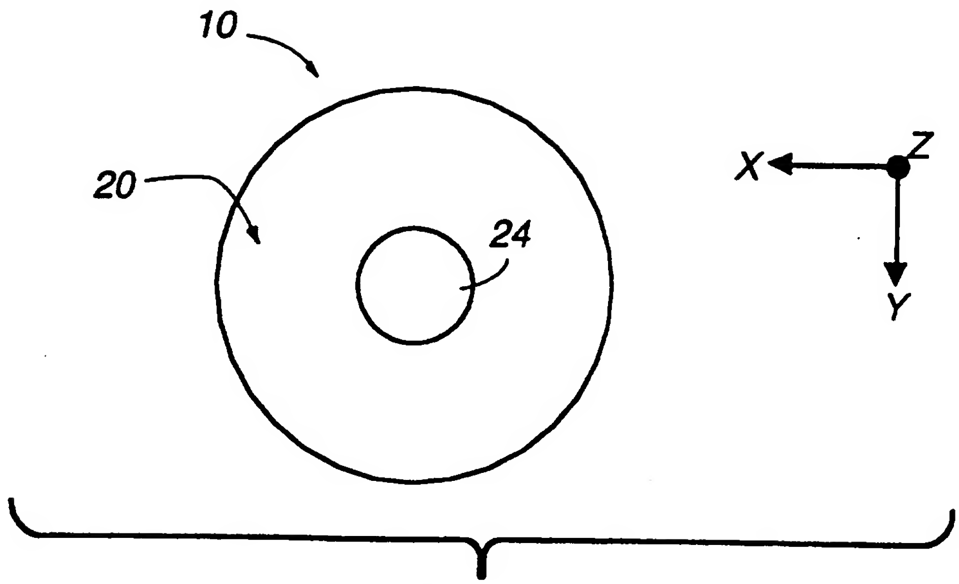


Fig. 3

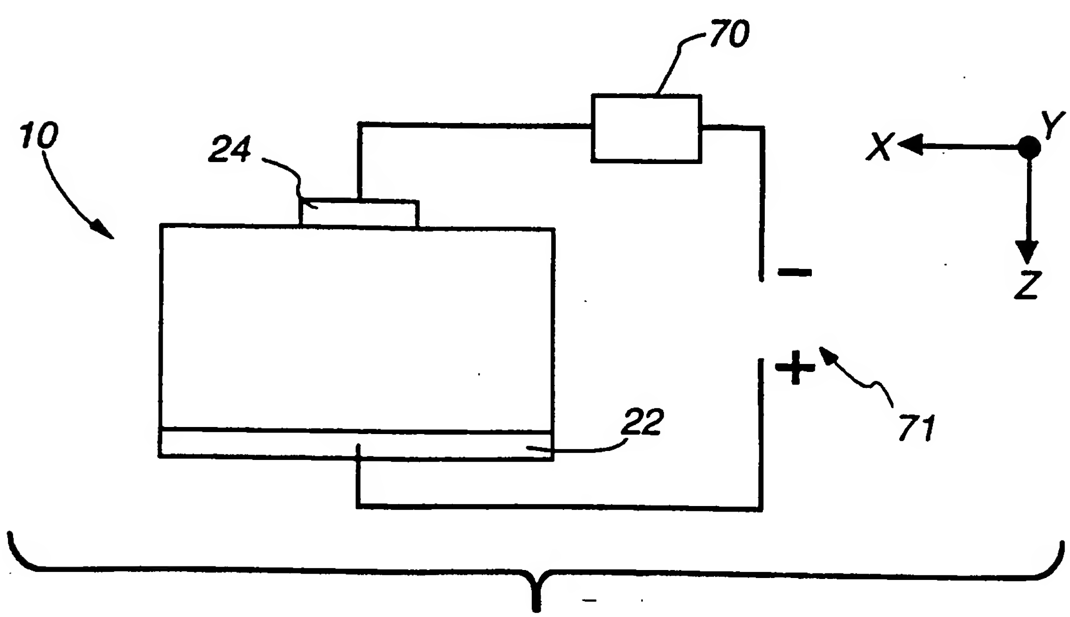


Fig. 4

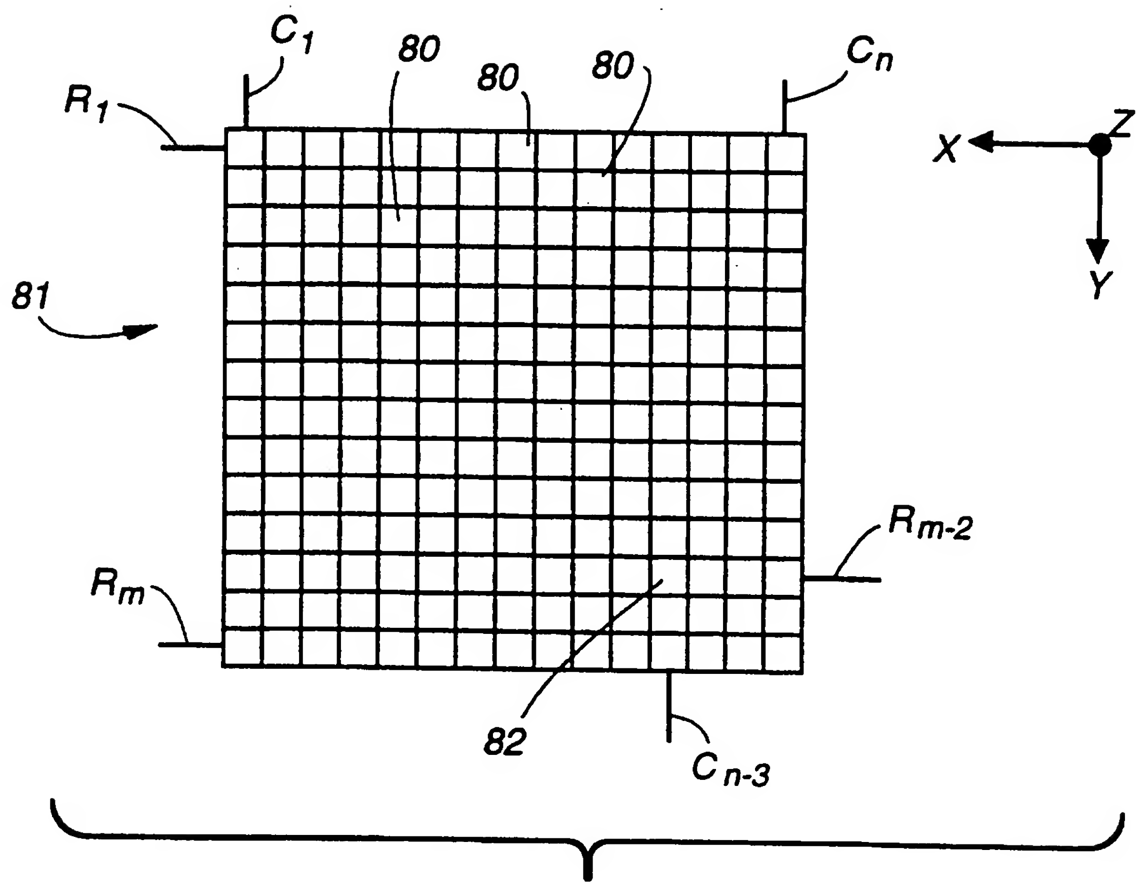

C1
80
80
80
Cn
R1
X
Z
Y
81
Rm-2
Rm
82
Cn-3

Fig. 5

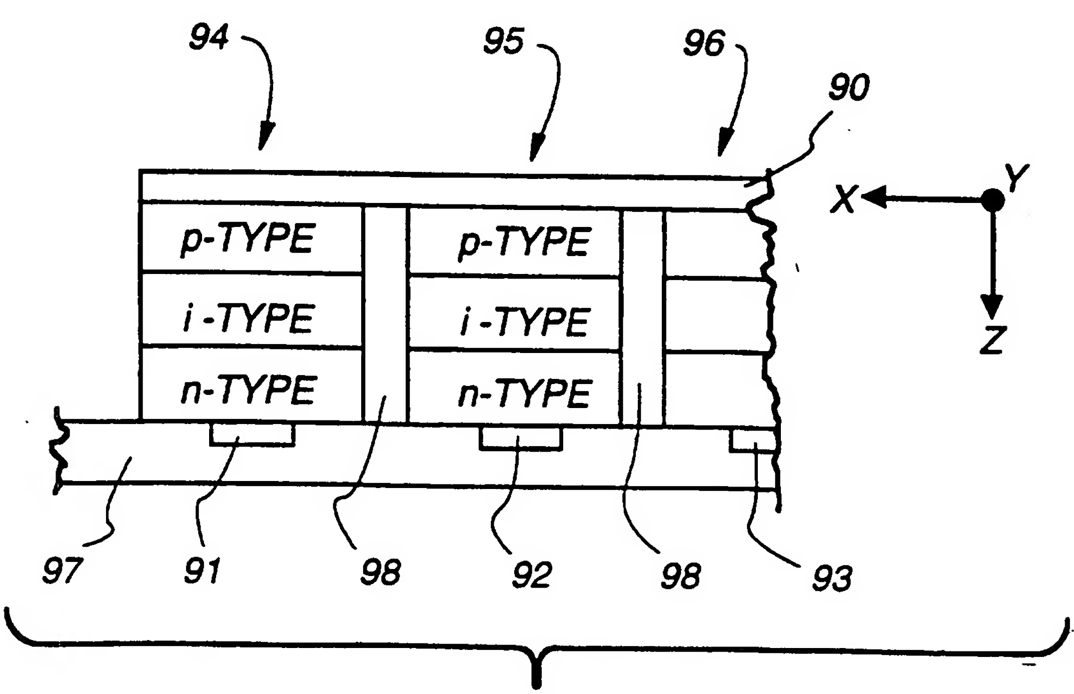
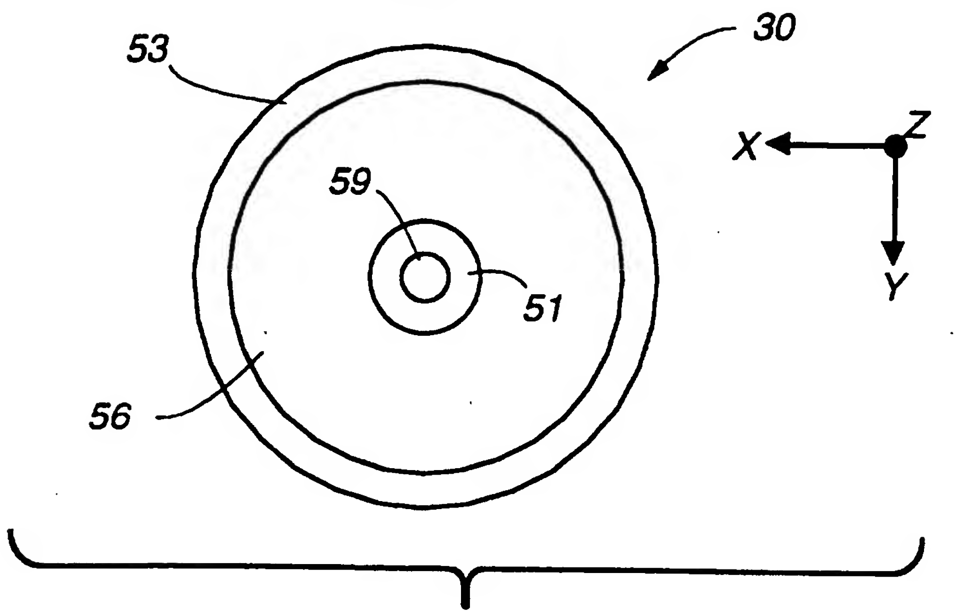
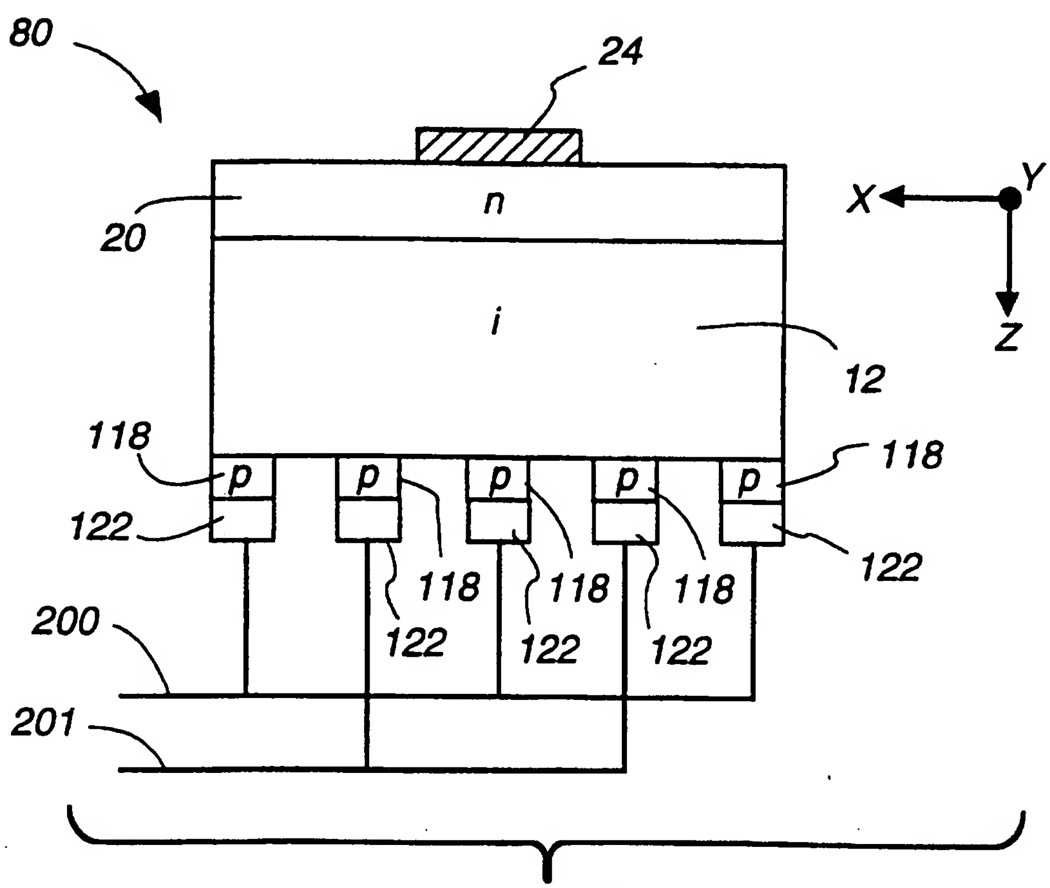

94
95
96
90
X
Y
Z
p-TYPE
i-TYPE
n-TYPE
p-TYPE
i-TYPE
n-TYPE
97
91
98
92
98
93

Fig. 6



30
53
59
51
56
X
Z
Y

Fig. 7



80
24
n
20
i
12
X
Y
Z
118
p
p
p
p
p
118
122
118
118
118
122
122
122
122
122
200
201

Fig. 8

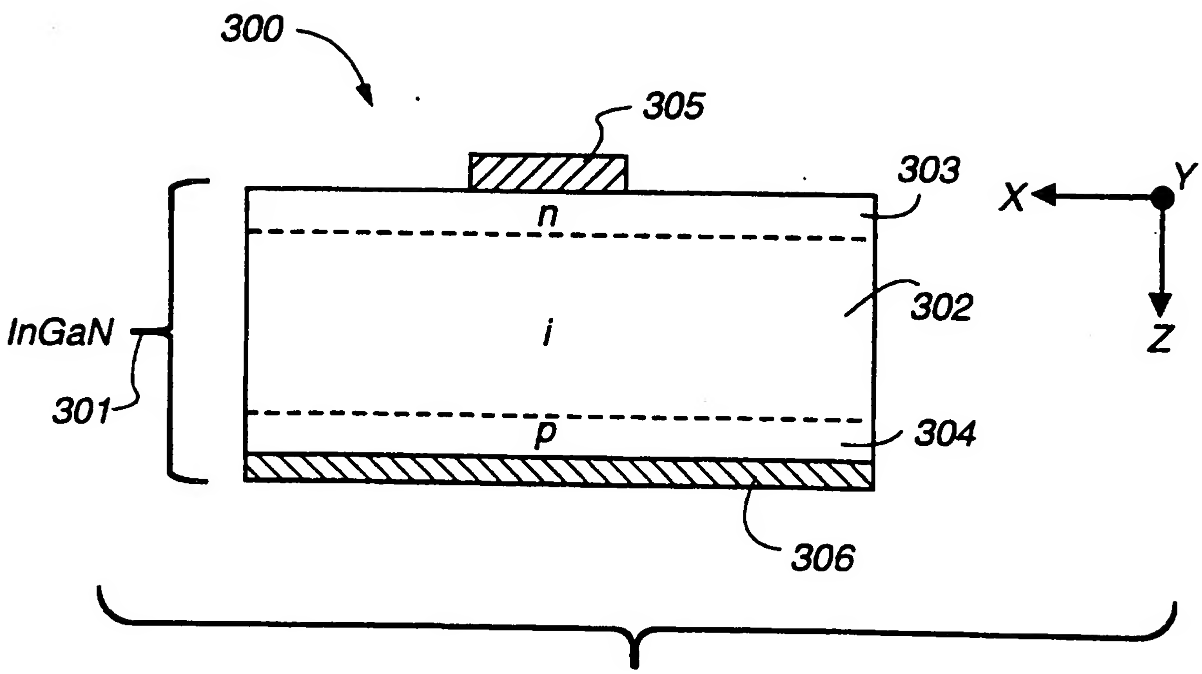

300
305
303
X
Y
Z
n
i
302
InGaN
301
p
304
306

Fig. 9

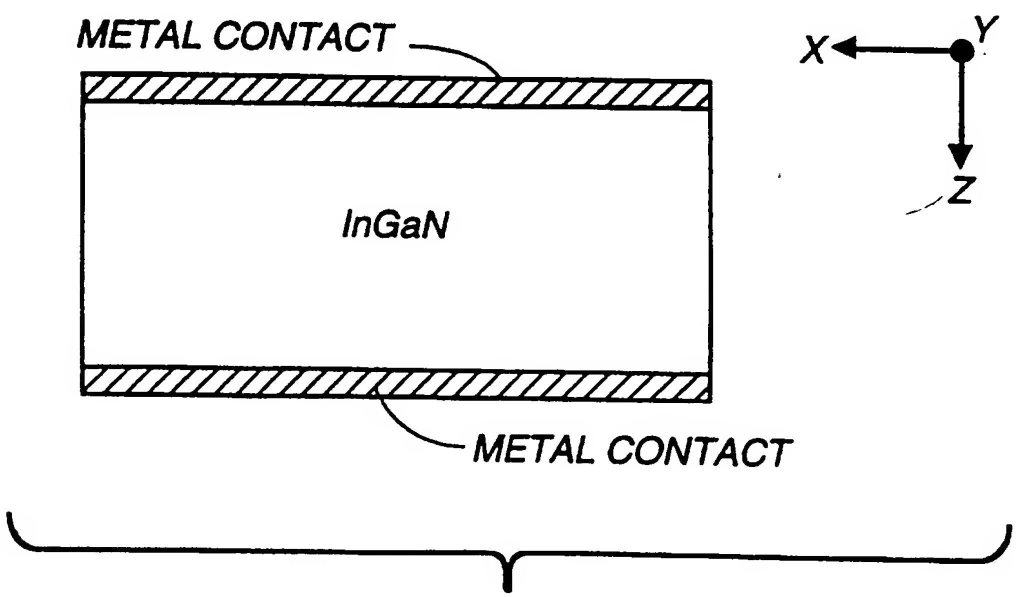

METAL CONTACT
X
Y
Z
InGaN
METAL CONTACT

Fig. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/15036

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01L 27/14, 31/00
US CL :257/428
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 257/428, 430, 443, 458

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS
search terms: X-ray detector, PIN diode, array, aluminum gallium nitride

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,448,099 A [Yano] 05 September 1995, abstract, cover Figure.	1, 16, 24 - 27
Y	US 4,710,589 A [Meyers et al] 01 December 1987, abstract, Figure 2.	1, 16, 24 - 27
Y	US 5,465,002 A [Snoeys et al] 07 November 1995, column 1, lines 14 - 42.	16 - 24
Y	US 5,355,103 A [Parker] 11 October 1994, abstract.	16 - 24
Y	US 5,530,267 A [Brandle, Jr. et al] 25 June 1996, column 6, lines 32 - 40.	1 - 15
A	US 5,433,169 A [Nakamura} 18 July 1995, column 3 line 32 - column 5, line 63.	1 - 15, 17

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 FEBRUARY 1997	04 MAR 1997

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